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Replication quality control of metal and polymer micro structured optical surfaces

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ABSTRACT

Non contact measurements are preferred for the characterization of ultra-finely finished surfaces which is particularly challenging if damages of the structures should be avoided. However, it is not always possible to use these methods because low roughness in metallic materials, as optical surfaces, quite often results in mirror-like surfaces which scatter the light and invalidate the optical measurements. This paper focuses on an analysis of a micro-structured optical component and the corresponding mould. A first investigation leads to a control of the manufacturing process through a control of the product. The purpose is to evaluate three critical dimensions. Results show that the difference of the measurements on different areas of the mould and the polymer component is approximately 4%. A second analysis focuses on the investigation of the optical component and its mould using replication methods based on polymer casting. The replica method is used in order to avoid damages of the structures and make feasible the measurement of optical specimens with non-contact instruments. Results show a quality replication equal to 95 - 99%. In both investigations the uncertainty of the measurements is assessed following the substitution method.

Keywords: replication quality control, surface metrology, optical surfaces.

1. INTRODUCTION

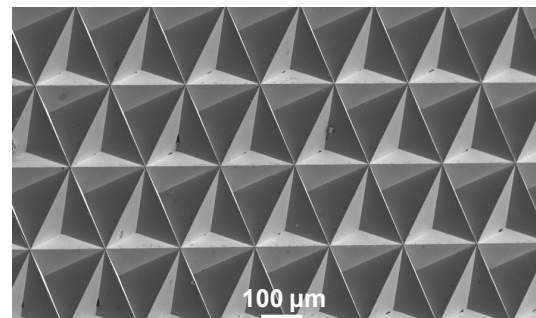
Quality control of optical surface structures is a challenging task in terms of characterization using tactile or optical instruments. The tactile measuring machines could damage the surface, while the optical ones could lead to wrong measurements for a bad reflection of the light. New techniques for near-surface characterization are emerging, especially regarding the difficulties in measurement, or when the definition of new, sound procedures are required [1]. A way to overcome the challenge of optical structure characterization is to replicate the optical components using polymer casting. The replication method has been used for different topography purposes of: skin surfaces [2]; machined parts as steel sheets, a cylinder line, a crankshaft and a face-ground surface [3]; and biological structures [4].

For the case study of the present paper, two samples are taken into account: a micro-structured optical component and its mould, characterized by triangular micro-pyramidal structures as shown in Fig. 1.

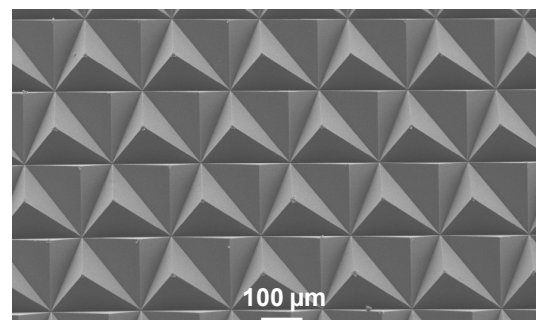
The aim of the investigation is to characterize the two samples through dimensional measurements of three critical features. Therefore the measurements results obtained from the optical component are compared with the one achieved from the mould characterization in order to perform a quality control of the manufacturing process through a control of the product.

A further investigation interests the application of the replication method on the mould and on the polymer

component. Again measurements are performed in order to analyze and evaluate the feasibility of the replication technique.



(a)



(b)

Fig. 1: SEM images of the nickel mould (a) and the PMMA polymer part (b).

Finally, for both investigations the uncertainty of the measurements is assessed following the Guide to the Expression of Uncertainty in Measurements (GUM) [5] and the substitution method applied to coordinate measuring machines (CMMs) (i.e. ISO/TS 15530-3:2004) [6].

2. EXPERIMENTAL WORK

2.1. Tooling

The mould is in nickel (Ni) made through an electroforming process. The used master is in aluminium realized using diamond cutting technology and subsequently replicated by nickel electroforming (see Fig.2). Special machining is requested in order to obtain ultra-high-accuracy cavities. Very low surface roughness suitable for optical applications ($R_a = 2-5$ nm), and very high form accuracy (form error < 20 nm) can be achieved using diamond cutting [7; 8; 9; 10].

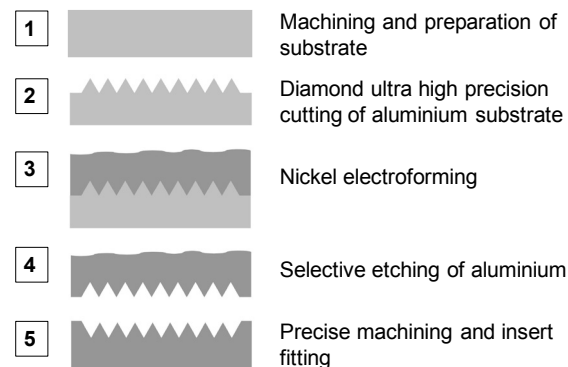


Fig. 2: Tooling process chain for the manufacturing of micro structured mould for optical applications: diamond ultra high precision cutting of aluminium substrate, nickel electroforming, selective etching of aluminium, precise machining and insert fitting.

2.2 Injection Compression Moulding

The optical parts are produced through an injection compression moulding process using polymethyl-methacrylate (PMMA, ALTUGLASS V 825 T grade) as polymer material. The injection compression moulding process leads to high accuracy replication of micro structures and a surface finishing suitable for optical applications [11; 12].

The injection compression technology can be considered a natural extension of the traditional injection moulding process for thermoplastic materials and it is characterized by two phases, see Fig. 3:

1. **INJECTION:** during this phase the mould cavity is kept partially open to facilitate the flow of plastic inside the cavity. Mechanical solutions are designed for the closure of the cavity in order to prevent the spillage of the polymer outside the mould.
2. **COMPRESSION:** during the injection phase or at the end of the injection phase, the machine closing force reduces the thickness of the mould cavity to the real

thickness of the component and the polymer is driven inside the empty region of the cavity. This phase produces a uniform distribution of the pressure into the mould cavity, unlike traditional injection moulding where a gradient of pressure occurs.

The main advantages and the main applications of the injection-compression moulding are reported in Table 1.

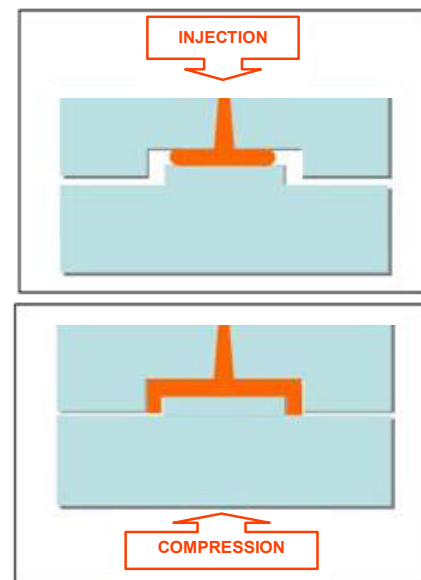


Fig. 3: Two stages of the injection compression moulding process.

Table 1: Advantages and main applications of injection compression moulding.

Advantages

With respect to traditional injection moulding:

- high quality elements
- homogeneous physical properties
- dimensional stability
- good control on the residual stresses
- low volumetric shrinkage
- improved mould cavity replication

With respect to moulding technology:

- low-cost (comparable with traditional injection moulding)
- high rate process (cycle times slightly lower compared to injection moulding)

Applications

Advantageous technique for:

- high thickness lenses
- components with small cavity to be filled (e.g. Fresnel lenses)
- elements with micro-structures (e.g. CD, DVD, Blu-Ray disc)
- thin wall components
- components with both thin and thick parts

2.3 Replica Moulding

The replica production is performed using a compound supplied in cartridges containing both the polymer and the curing agent, which are automatically mixed in a disposable static-mixing nozzle during the application to the surface. The involved compound is a blue hard material made by acrylic resin, glass powder and silica used for dental applications; previously investigated for width dimensions of 2 - 4 mm in [13; 14].

2.4 Measurements

The micro-pyramidal structures of the mould, the polymer part and the replicas are characterized through the analysis of SEM (Scanning Electron Microscope) images. The measurements of the specimens are carried out on ten different areas (A, B, ... , L), represented in Fig. 4; on each area three different features were taken into account and analyzed using an image processor software, called Scanning Probe Image Processor [15].

Referring to Fig. 4, the three investigated features are:

- Vertical pitch (1-2): 21 vertical pitch measurements were carried out for each area and the average was calculated;
- Diagonal pitch (2-3): 24 diagonal pitch measurements were carried out for each area and the average was calculated;
- Horizontal pitch (3-4): 42 horizontal pitch measurements were carried out for each area and the average was calculated.

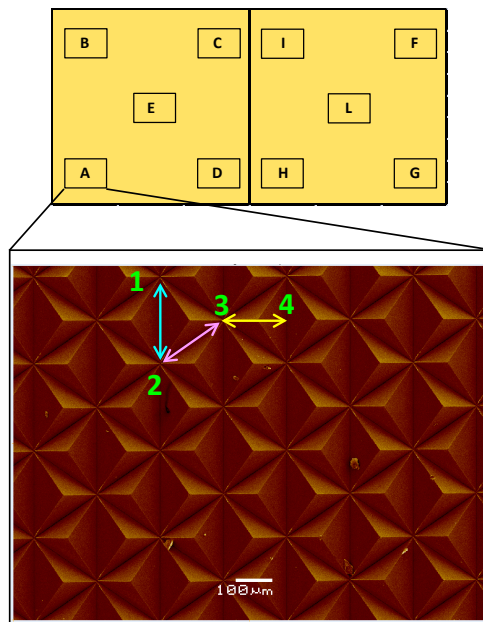


Fig. 4: Ten areas (A, B, ..., L) investigated on the parts and the three measured pitches: vertical (1-2), diagonal (2-3) and horizontal (3-4).

3. MANUFACTURING PROCESS CONTROL

The quality control of the manufacturing process is performed through a control of the product. For this reason the achieved measurements on the mould and on the polymer part are compared and graphically represented in Fig. 5.

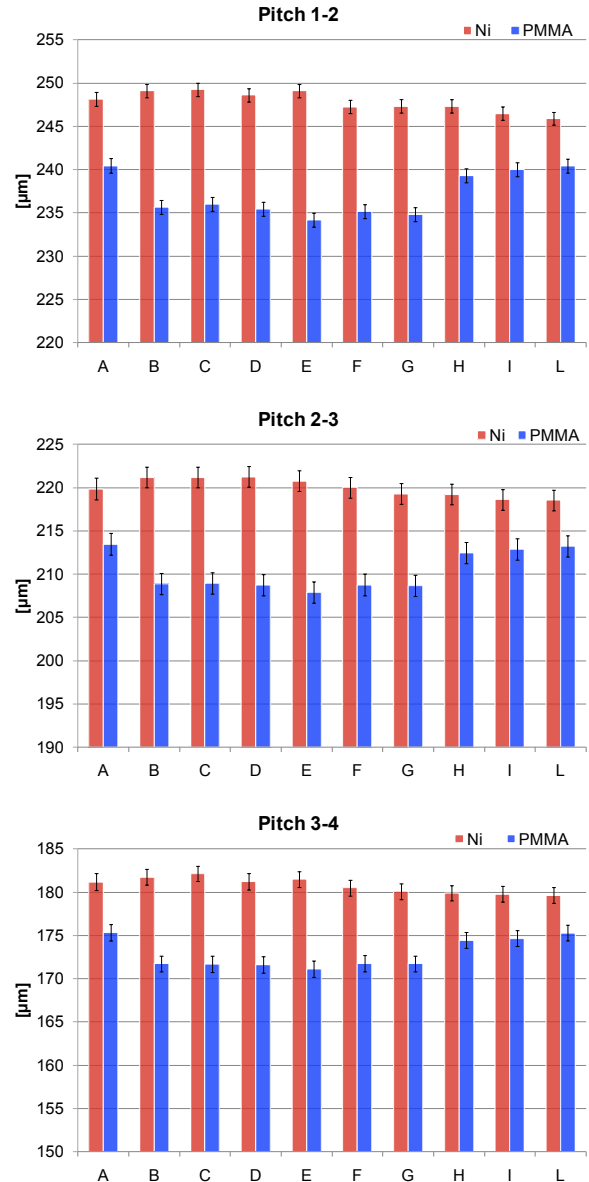


Fig. 5: Comparison between the measured pitches on the mould (red columns) and on the polymer part (blue columns): vertical pitch (1-2); diagonal pitch (2-3) and horizontal pitch (3-4).

Taking into account the results obtained from the mould measurements (red columns on Fig. 5), the pitch lengths of any area appear to be in the same range and to be in average equal to 250 μm (vertical pitch 1-2), 220 μm (diagonal pitch 2-3) and 181 μm (horizontal

pitch 3-4). Moreover the vertical pitch has larger dispersions of the values due to the machining process: the reason is that the vertical pitches are the result of the intersections between the vertical and the diagonal features as it is visible from Fig. 4.

The results obtained from the measurements on the polymer component (blue columns on Fig. 5) show that the deviation from the mould values is approximately 3-5% and equal to 6 - 11 μm . This deviation is due to the polymer shrinkage occurring during the cooling phase after the mould filling.

Moreover looking at Fig. 5 and 6, the same trend is found on the same area of the different pitches. This proves that the shrinkage depends on the different location inside the mould. If there is a non-uniform temperature and pressure distribution in the cavity, the shrinkage will be unbalanced due to polymer compressibility (i.e. specific volume depends on both pressure and temperature).

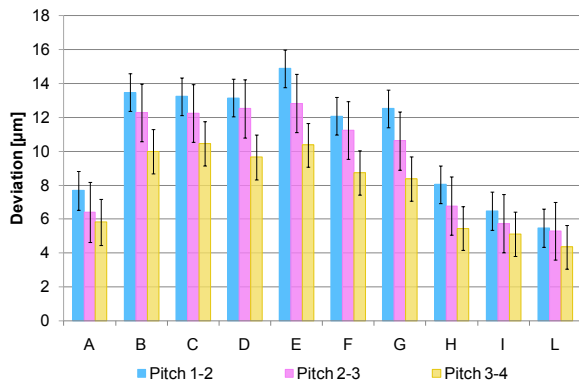


Fig. 6: Deviation of the measured pitches on the polymer part respect to the measured pitches on the mould: vertical pitch (1-2); diagonal pitch (2-3) and horizontal pitch (3-4).

4. REPLICATION QUALITY CONTROL

After the quality control of the manufacturing process, the replica technique based on polymer casting was performed on the mould and on its optical component in order to investigate the quality control of the replication technique. The measurements on both replicas were taken and analyzed as described in paragraph 2.4 and they are compared and graphically represented in Fig. 7 and 8.

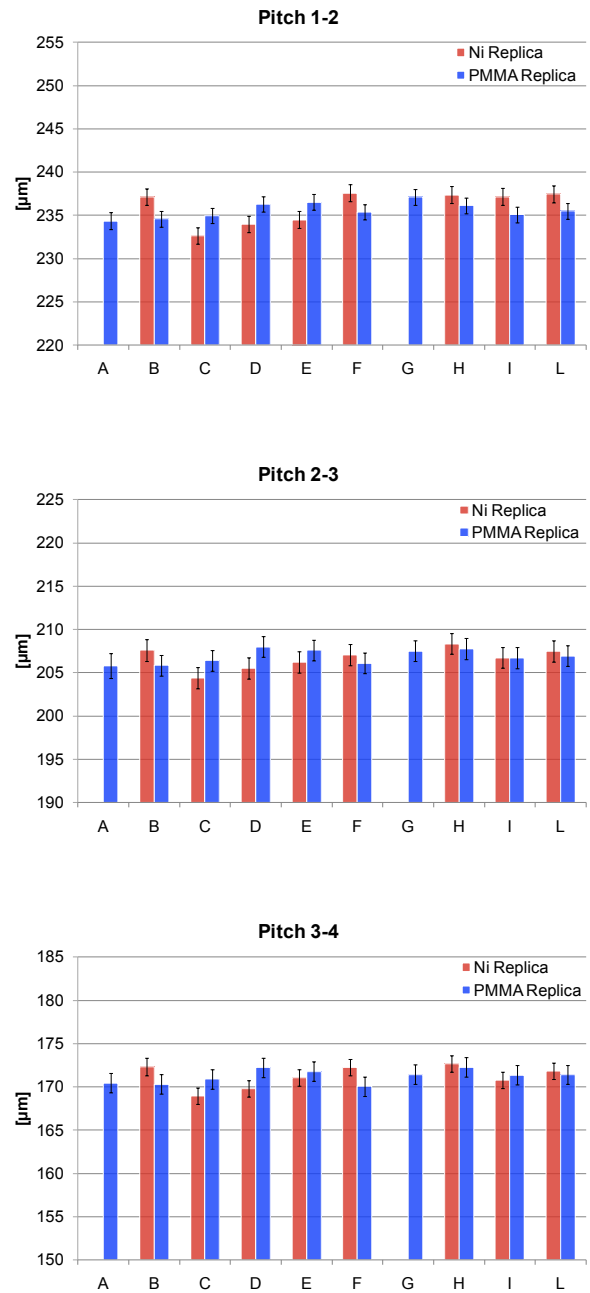


Fig. 7: Comparison between the measured pitches on the replica mould (red columns) and on the replica of the polymer part (blue columns): vertical pitch (1-2); diagonal pitch (2-3) and horizontal pitch (3-4). A and G areas were not measured.

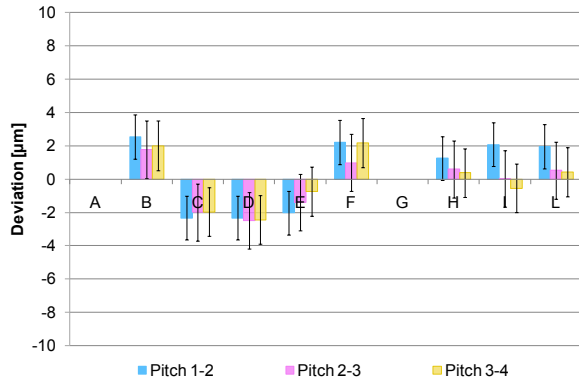


Fig. 8: Deviation of the measured pitches on the polymer part replica respect to the measured pitches on the mould replica: vertical pitch (1-2); diagonal pitch (2-3) and horizontal pitch (3-4).

The results achieved on the replica mould (red columns on Fig. 7) are spread equally on the same area of the different pitches and they are equal to 236 µm (vertical pitch 1-2), 207 µm (diagonal pitch 2-3) and 171 µm (horizontal pitch 3-4). These values are 95% of the ones obtained from the mould measurements as shown in Table 2. A better quality replication (99%) is achieved for the replica part as it is shown in Table 3.

The results prove that this kind of replication technique represents a promising method to evaluate and characterize surfaces that are difficult to measure.

Table 2: Comparison between the pitches measured on the mould and on the replica mould.

| | Pitch 1-2 | Pitch 2-3 | Pitch 3-4 |
|--------------------|-----------|-----------|-----------|
| Mould [µm] | 250 | 220 | 180 |
| Replica mould [µm] | 236 | 207 | 171 |
| % | 94,4 | 94,1 | 95,0 |

Table 3: Comparison between the pitches measured on the polymer part and on the replica part.

| | Pitch 1-2 | Pitch 2-3 | Pitch 3-4 |
|-------------------|-----------|-----------|-----------|
| Part [µm] | 237 | 210 | 173 |
| Replica part [µm] | 236 | 207 | 171 |
| % | 99,6 | 98,6 | 98,8 |

5. UNCERTAINTY BUDGET

The uncertainty budget for width and length (Eq. 1) is calculated following the Guide to the Expression of Uncertainty in Measurements (GUM) [5] and the

substitution method applied to coordinate measuring machines (CMMs) (i.e. ISO/TS 15530-3:2004) [6].

$$U_i = k \cdot \sqrt{u_{res}^2 + u_{c,i}^2 + u_{cal}^2 + u_{SEM,i}^2 + u_{magn}^2} \quad (1)$$

With:

$$u_{SEM,i} = \max(u_{rep}; u_{area}) \quad (2)$$

Where:

- U = expanded combined uncertainty;
- $i = x, y$ depending on the measurand (x for horizontal pitch; y for vertical pitch; xy for diagonal pitch);
- $k = 2$ in order to obtain a confidence level of approximately 95%;
- u_{res} = instrument resolution;
- $u_{c,i}$ = calibration uncertainty;
- u_{rep} = repeatability (Eq. (2)) = standard deviation of three measurements carried out on the same five pitches;
- u_{area} = standard deviation of all the pitches measured in the same area;
- u_{magn} = deviation between the nominal pixel size and the measured one according to [16].

Measurements on the same pitches as well as on different pitches of the components are affected by instrument repeatability. Therefore, the maximum value among the uncertainty contributors (u_{rep} , u_{area}) was selected to not overestimate the repeatability.

For each measurement performed on the mould, on the optical component, on the replica mould and on the replica part, the uncertainty budget is calculated according to Eq. (1) and the average of the different uncertainties is listed in Table 4. The uncertainties calculated for the mould and the part measurements appears to be 0,5% of the measured pitches; while the uncertainties calculated for the replica mould and the replica part are 0,6% of the measured pitches.

Table 4: Average of the uncertainty budgets calculated for the different pitches measured on the ten areas of the corresponding component.

| U [µm] | Pitch 1-2 | Pitch 2-3 | Pitch 3-4 |
|---------------|-----------|-----------|-----------|
| Mould | 0,8 | 1,2 | 0,9 |
| Part | 0,8 | 1,2 | 0,9 |
| Replica mould | 1,0 | 1,2 | 1,0 |
| Replica part | 0,9 | 1,2 | 1,1 |

6. CONCLUSIONS

The purposes of the paper were to perform a quality control of the manufacturing process through a control of the product and to evaluate the feasibility of a replication technique.

The selected case study was an optical component and its mould characterized by micro-pyramidal features, which were replicated afterwards using polymer casting. For the investigation three critical dimensions (vertical, horizontal and diagonal pitch) were chosen and measured using SEM images processing.

Results showed an accurate manufacture of the mould and a good replication quality of the optical component through injection moulding: the pitch deviation between the mould and the polymer part resulted 3 - 5%. This deviation is due to the polymer shrinkage occurring during the cooling after the mould filling, but also to the different flow conditions of the polymer inside the mould during filling, packing and cooling phases. According to these results further analysis will be required in order to evaluate height and angles of the pyramidal features in both the samples. The aim is to have a complete characterization of the optical components and its mould.

A further investigation was developed with the aim of quantify the feasibility of a replication technique which uses blue hard material made by acrylic resin, glass powder and silica. The replication degree appears to be 95% for the replica mould and 99% for the replica part. The results prove that the investigated method is suitable to evaluate and characterize surfaces that are difficult to measure. Further researches will interest the use of soft polymer casting in connection to the new required measurements which involve height and angles characterization and, moreover, in order to analyze other polymer casting materials.

Finally, in both analysis the uncertainty of the measurements was assessed following the substitution method and resulted to be 0,5 - 0,6% of the measured pitch. The uncertainty assessment can be a challenging task for measurements in the sub-mm down to sub- μ m dimensional ranges. Therefore the scopes of the analysis were to propose a useful guideline to identify the uncertainty contributors to be taken into account during the uncertainty budget as well as to provide a viable method for the uncertainty calculation for measurements in the 100-200 μ m range.

7. ACKNOWLEDGEMENTS

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